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# Cost–Benefit Analysis of Mulch Film Management and Its Policy Implications in Northern China

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**Abstract:** Agricultural white pollution is a pressing concern in China. However, the efficiency and rationality of the government's subsidies for mulch film management remain ambiguous. To formulate reasonable policies for mulch film management and optimize fiscal resource allocation, the study employs cost–benefit analysis to evaluate the economic performance of mulch film management. Two environmentally friendly measures being primarily proposed in China, namely the application of thicker mulch film (hereinafter referred to as thicker film) and the substitution of biodegradable mulch film (hereinafter referred to as biodegradable film), are selected for analysis, with conventional mulch film (hereinafter referred to as conventional film) serving as the benchmark for comparison. Primary data obtained through field surveys, supplemented by secondary data from national statistics, industry reports, and literature reviews, are used for the study. Results show that thicker film application is cost-effective, with a net benefit of CNY 3208.8/ha (USD 449.2/ha; 1 CNY = 0.14 USD), which is CNY 253.8/ha (USD 35.5/ha) higher than that of conventional film. The net benefit for biodegradable film application is lower than that for conventional film, at CNY 2244.6/ha (USD 314.2/ha). The results reveal the significant potential of promoting the use of thicker film due to its recycling and economic advantages. Findings imply that the further promotion of its use lies in improving farmers' cognition and optimizing subsidy dimensions to allocate government financial resources more effectively. On the contrary, biodegradable film utilization is unprofitable and relies on continuous external subsidies. The government can optimize the subsidy standard based on the cost–benefit performance of different mulch films applied and provide incentives to promote cost reductions and efficiency increases. Further analysis indicates that sustainable mulch film management entails developing mechanisms to internalize the external benefits of management and innovating a new governance landscape.

**Keywords:** mulch film management; cost–benefit analysis; thicker mulch film; biodegradable mulch film; policy implication

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## 1. Introduction

As a pivotal agricultural technique, mulch film application has revolutionized the conventional agricultural landscape, ushering in profound changes to agricultural production patterns and regional planting structures [1,2]. Owing to its exceptional capabilities in soil warming, moisture conservation, and weed prevention, mulch film has the potential to elevate crop yields by 20–50% [3,4], thereby bestowing upon Chinese agriculture direct economic benefits ranging from CNY 120 to 140 billion (USD 16.8 to 19.6 billion) annually [5]. Nevertheless, over the span of more than forty years of utilization, insufficient environmental consciousness and disregard for recycling have precipitated the massive accumulation of residual plastics in farmland [6], resulting in a litany of issues, including soil degradation, yield constraints, and microplastic contamination [7]. The "White revolution" is deteriorating into "white pollution".

The Chinese government has progressively prioritized agricultural plastic waste management in the past decade. Since 2022, authorities have initiated the pilot demonstration of "mulch film scientific utilization and recycling" in nine provinces (autonomous regions) where mulch film is intensively utilized, with the pilot area accounting for 2.9% of the nationwide farmland. The pilot emphasizes two main environmentally friendly mulch film management practices. These include, firstly, advocating for thicker mulch film (hereinafter referred to as thicker film) application (Figure 1). Typically, the mechanical strength of mulch film declines after several months to one year of utilization, making it challenging to collect and reprocess, while increasing the thickness can significantly enhance its recyclability [8]. The thickness of pilot-endorsed thicker film measures 0.015 mm. This surpasses the conventional mulch film (hereinafter referred to as conventional film) thickness of 0.010 mm, which is the current Chinese national standard [9]. Evidence suggests that thicker film has a recovery rate of over 90%, far exceeding that of conventional film at 30% [10]. The other practice is promoting biodegradable mulch film (hereinafter referred to as biodegradable film) application. Composed primarily of polysaccharides and polyesters, biodegradable materials theoretically have the potential to break down into $H_2O$, $CO_2$, and microbial biomass within a reasonable time frame [11]. After crop harvest, biodegradable film is plowed into the soil and is expected to decompose over time, eliminating any need for recycling.

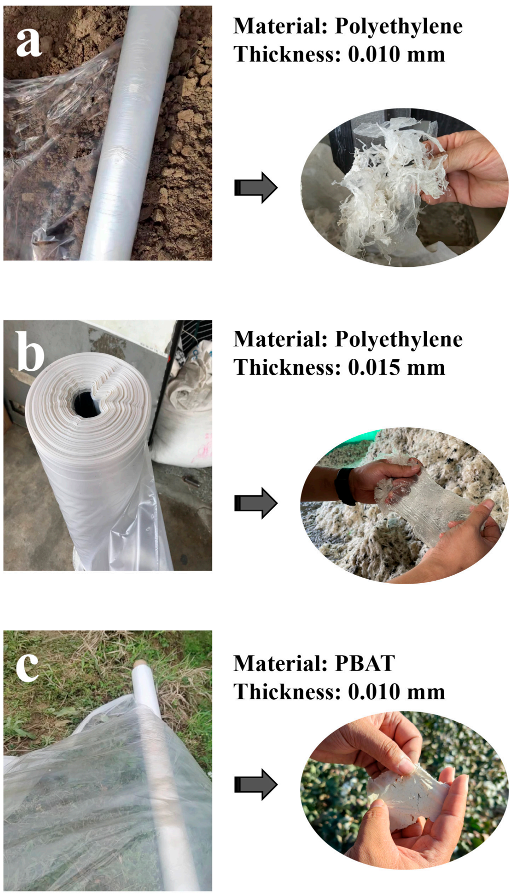


**Figure 1.** Comparison of three types of mulch film: (**a**) conventional film, (**b**) thicker film, and (**c**) biodegradable film.

Thicker film and biodegradable film lead to discernibly higher utilization expenses compared with those of conventional film owing to their elevated consumption volume and price per farmland area. Applying these two types of mulch film undoubtedly increases the economic strain on users, thereby dampening their enthusiasm for adoption. In order to incentivize farmers to use such films, the government provides subsidies of CNY 450/ha (USD 63/ha) for thicker film and CNY 1800/ha (USD 252/ha) for biodegradable film to offset the additional expenses. The Chinese government is ambitious in beating agricultural white pollution, aiming to scale up the pilot area to 15 million hectares by 2025, covering over 85% of the national mulching farmland. Under the current subsidy standards, the government is required to allocate almost CNY 10 billion (USD 1.4 billion) for mulch film management, which is more than 3.0% of its investment in environmental protection [12]. It should be acknowledged that mulch film management is only one aspect of environmental governance in China, and such significant financial expenses are obviously unsustainable. Especially given the current slowdown in economic growth and tight balance of financial circumstances, there is a growing emphasis on efficiently allocating financial resources.

Reasonable subsidies constitute a pivotal aspect influencing the effectiveness of government policies [13]. An excessive subsidy for mulch film management may increase the financial burden on the government and impede the efficiency of fiscal resource allocation, while an insufficient subsidy could diminish the proactive engagement of farmers, obstructing the attainment of management objectives. It is essential to strike a balance between governments and other stakeholders in mulch film management expenditure. Thus, what is the economic performance of different environmentally friendly mulch film management practices? How reasonable are the current subsidy standards for mulch film management? Are the subsidies precisely targeted? Can the management mechanism be further refined to optimize government functions? Information on the cost-effectiveness of mulch film management can provide the foundation for addressing these inquiries [14]. To this end, cost–benefit analysis is adopted to analyze the benefits and costs of mulch film management to improve the understanding of its economic performance [15,16], to optimize mulch film management policies, and to formulate a sustainable management mechanism based on this information. The cost–benefit analysis is conducted in four provinces (autonomous regions) in the north of China: Xinjiang, Gansu, Ningxia, and Inner Mongolia (Figure 2). This region is the largest cotton-cropping area and a significant corn and potato cropping area in China, representing remarkably typical and representative scenarios of mulch film application [17]. Moreover, the frigid and arid climate here renders mulch film an essential agricultural input. Statistics reveal that approximately 30% of farmland in the region is covered by mulch film, far exceeding the national average of 12%. Annually, around 446,080 metric tons of mulch film is utilized in the region, making up over one-third of the total consumption in China [18]. Correspondingly, the region faces severe mulch film waste and urgent agricultural white pollution control challenges [19]. The Chinese government has piloted 2.0 million hectares of thicker film and 106,667 hectares of biodegradable film across the four provinces (autonomous regions). The region accounts for nearly 60% of the overall pilot area despite comprising only 20% of the national farmland.

In summary, the goal of this study is to establish an economic decision-making model by employing cost–benefit analysis to systematically assess the economic performance of mulch film management and provide detailed information on the cost–benefit correlation of different management measures. Evaluating the economic feasibility of various mulch film management strategies can provide a scientific reference for current mulch film policies and provide insights for restructuring regulatory frameworks and modifying incentives to allocate fiscal resources more efficiently, hence enhancing support for agricultural white pollution control. This is of significant theoretical and practical importance for improving the agricultural ecological environment and facilitating integrated economic, social, and environmental development.

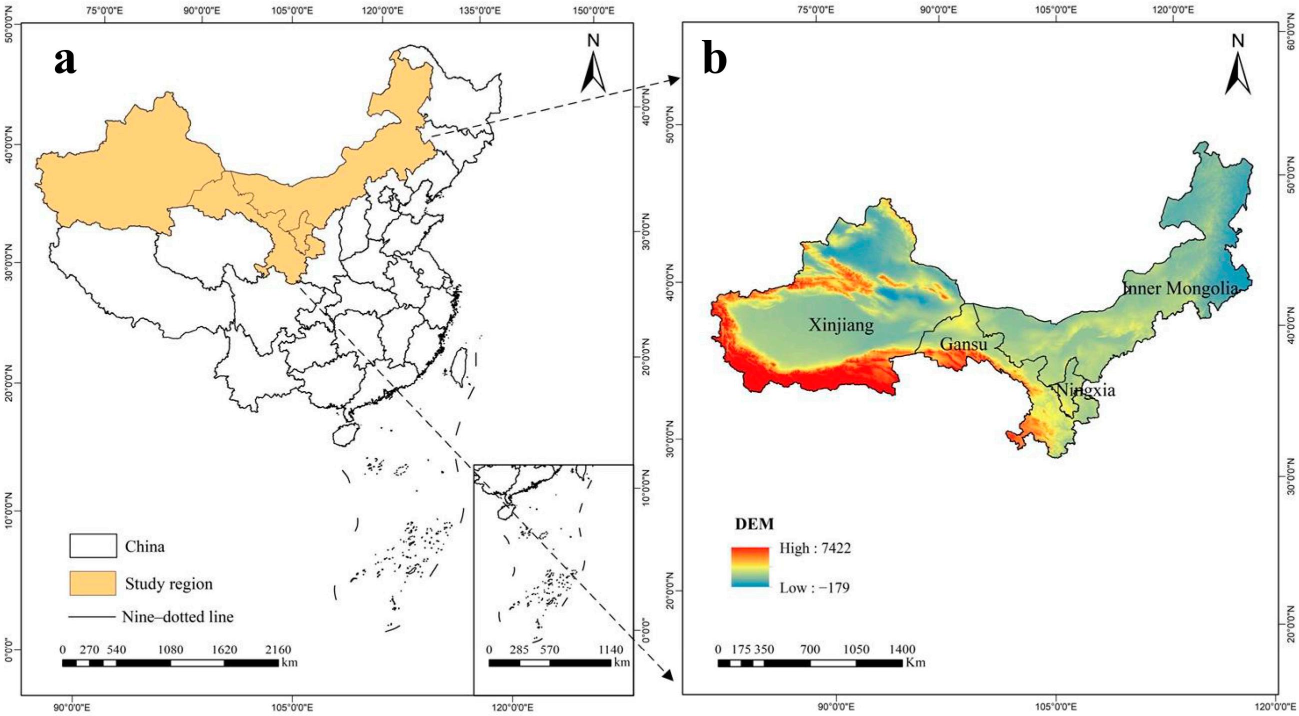


**Figure 2.** The study region: (**a**) the location of the study region in China; (**b**) the study regions of Xinjiang, Gansu, Ningxia, and Inner Mongolia.

## 2. Methods

### *2.1. Cost–Benefit Model of Mulch Film Management*

This study conducts cost–benefit analysis of mulch film management, focusing on two specific environmentally friendly measures: the application of thicker film (Option 1) and that of biodegradable film (Option 2), with the application of conventional film (Baseline) as the benchmark for comparison. The management process consists of three key stages: procurement, utilization, and treatment. Meanwhile, external costs that are not captured in financial expenditures are taken into account in the study. Drawing upon the methodologies applied previously regarding cost–benefit analysis [20–23], this study employs the net present value (*NPV*) and the benefit–cost ratio (*BCR*) to characterize the comprehensive performance associated with mulch film management. The equations for calculating *NPV* and *BCR* are as follows:

$$NPV = \sum_{t=0}^{X} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{X} \frac{C_t}{(1+r)^t} \quad (1)$$

$$BCR = \left(\sum_{t=0}^{X} \frac{B_t}{(1+r)^t}\right) / \left(\sum_{t=0}^{X} \frac{C_t}{(1+r)^t}\right) \quad (2)$$

where $X$ represents the project's time span, $t$ stands for time, and $B_t$ and $C_t$ denote the benefits and costs in year $t$, respectively. $r$ is the social discount rate.

*NPV* is the summation of the present values (PVs) for future cash flows [24]. The most economically advantageous mulch film management measure is the one with the highest positive *NPV*. Similarly, if a project has a *BCR* greater than 1.0, it is expected to deliver a positive *NPV* to a firm and its investors [25].

### 2.2. Costs of Mulch Film Management

$C_{management}$ represents the costs of mulch film management. As stated above, $C_{management}$ mainly consists of the procurement cost ($C_{procurement}$), utilization cost ($C_{utilization}$), and treatment cost ($C_{treatment}$). $C_{management}$ is the sum of these three components:

$$C_{management} = C_{procurement} + C_{utilization} + C_{treatment} \tag{3}$$

#### 2.2.1. Procurement Costs

$C_{procurement}$ is the cost incurred during the purchase of mulch film by farmers. It depends on the unit price ($UP_{mulching}$) of the mulch film, the quantity of mulch film used per unit of farmland ($UQ_{mulching}$), and the mulching area ($S_{mulching}$). $C_{procurement}$ represents the multiplication of the three components:

$$C_{procurement} = UP_{mulch\ film} \times UQ_{mulching} \times S_{mulching} \tag{4}$$

#### 2.2.2. Utilization Costs

$C_{utilization}$ refers to the costs incurred during the mulching process. It mainly consists of two parts: Firstly, the transportation cost ($C_{transportation}$) incurred in transporting mulch film from manufacturer to farmland is referred to. $C_{transportation}$ is related to the quality of mulching per unit of farmland ($UQ_{mulching}$), the mulching area ($S_{mulching}$), the transportation distance from producer to farmland ($D_{transportation}$), and the unit transportation cost ($UC_{transportation}$). Secondly, the costs generated during the mulching process ($C_{mulching}$) are referred to, which include the fuel cost ($C_{fuel}$) and labor cost ($C_{labor}$). External costs incurred during the transportation and mulching processes are also accounted for, namely the monetization of greenhouse gas (GHG) emissions from fuel consumption ($M_{GHG}$). This is assessed using the unit price for $CO_2$ ($UP_{GHG}$), the quality of fuel consumed ($Q_{fuel\ consumption}$), and its carbon emission factor ($EF_{fuel}$).

$$\begin{aligned} C_{utilization} &= C_{transportation} + C_{mulching} \\ &= UQ_{mulching} \times S_{mulching} \times D_{transportation} \times UC_{transportation} + \left(C_{fuel} + C_{labor}\right) \times S_{mulching} + M_{GHG} \end{aligned} \tag{5}$$

#### 2.2.3. Treatment Costs

In the case of conventional film, the collected residual film is transported to the fields or informal landfill sites around the farmland for landfilling. There are collection costs and transportation costs for the collected residual film, while the remaining film is left in the soil. Thicker film has good collectability and processability. The residual film is collected, transported to a mulch film processing plant, and recycled through a series of processes such as crushing, washing, melting, extruding, and so on. $C_{treatment}$ primarily encompasses the costs of mulch film waste collection ($C_{collection}$), transportation ($C_{transportation}$), and mechanical recycling ($C_{mechanical\ recycling}$). Biodegradable film is plowed into the soil after crop harvesting and decomposes completely without treatment.

$$C_{treatment} = C_{collection} + C_{transportation} + C_{mechanical\ recycling} \tag{6}$$

Similarly, the collection and transportation processes also entail economic and environmental costs. The economic costs are mainly labor and fuel costs. The environmental costs refers to the GHG emissions from fuel consumption.

$$C_{collection} = \theta \times UQ_{mulching} \times UC_{collection} \times S_{mulching} + M_{GHG} \tag{7}$$

$$C_{transportation} = (\theta \times UQ_{mulching} \times S_{mulching} \times D'_{transportation} \times UC_{transportation}) + M_{GHG} \tag{8}$$

where $\theta$ is the recovery rate of mulch film waste, $UC_{collection}$ is the unit price of mulch film collection, and $D'_{transportation}$ is the distance from the farmland to the treatment site.

In accordance with the project's financial analysis framework, $C_{mechanical\ recycling}$ comprises two main elements: capital costs and operating and maintenance costs [25,26]. Capital costs are the one-time expenditures derived from the land, plant, equipment and other fixed assets (Supplementary Material). In this study, capital costs are converted into annual costs by considering a 15-year depreciation period ($C_{depreciation}$). Operating and maintenance costs are annual ongoing expenditures, including equipment maintenance costs ($C_{equipment\ maintenance}$), labor costs ($C_{labor}$), enterprise management costs ($C_{\mathrm{enterprise}\ management}$), procurement costs of materials like water, energy, and mulch film waste ($C_{material}$), mulch film waste storage costs ($C_{storage}$), sludge removal costs ($C_{sludge\ removal}$) and taxes ($C_{tax}$).

$$C_{mechanical\ recycling} = C_{depreciation} + C_{equipment\ maintenance} + C_{labor} + C_{enterprise\ management} + C_{material\ procurement} + C_{storage} + C_{sludge\ removal} + C_{tax} \quad (9)$$

(1) Depreciation costs

$C_{depreciation}$ is estimated by employing the straight line method. Under straight-line depreciation, a fixed amount of depreciation is charged for each period throughout the project's life cycle. The cumulative amount equals the original value of the asset [27].

$$C_{depreciation} = (V_{initial} - V_{salvage})/n = [V_{initial} \times (1-\lambda)]/n \quad (10)$$

where $V_{initial}$ represents the initial value of the assets, $V_{salvage}$ represents the assets' salvage value, $n$ is the lifespan of the assets, and $\lambda$ is the salvage rate.

(2) Equipment maintenance costs

$C_{equipment\ maintenance}$ indicates the scheduled maintenance of the equipment. Maintenance costs are fixed throughout the lifespan. This value is calculated as a percentage, $\alpha$, of $C_{depreciation}$:

$$C_{equipment\ maintenance} = C_{depreciation} \times \alpha \quad (11)$$

(3) Labor costs

$C_{labor}$ is the cost incurred by employees. It is computed based on the average wages and the number of employees required. The number of employees depends on the enterprises' processing load and the working load of each employee.

$$C_{labor} = W_{local\ average} \times PC_{enterprise} \div L_{employee} \quad (12)$$

where $W_{local\ average}$ is the local average wage for the plastic recycling industry. $PC_{enterprise}$ is the enterprise's annual processing load, and $L_{employee}$ is the working load for each employee annually.

(4) Enterprise management costs

$C_{enterprise\ management}$ pertains to the daily expenses accrued by the administrative department of the enterprise in organizing production and operation activities. $C_{enterprise\ management}$ positively correlates with the number of employees. The study calculates it as a percentage, $\beta$, of $C_{labor}$ [28].

$$C_{enterprise\ management} = C_{labor} \times \beta \quad (13)$$

(5) Material costs

Different materials are required for the processing of mulch film waste. $C_{material}$ mainly includes electricity, fuel, and mulch film waste costs. It is calculated based on the quality of the treated plastic waste, the quantity of different materials required ($Q_{material}$), and the unit price of the material ($UP_{material}$):

$$C_{material} = \theta \times UQ_{mulching} \times S_{mulching} \times Q_{material} \times UP_{material} \quad (14)$$

where $Q_{material}$ is the quantity of material $k$ required to treat each unit of mulch film waste, and $UP_{material}$ is the unit price of material $k$. $k$ = 1, 2, 3 represents electricity, fuel, and mulch film waste, respectively.

(6) Mulch film waste storage costs

Generally, a certain amount of mulch film waste needs to be accumulated before it can be processed. Thus, storage costs are incurred. $C_{storage}$ is related to the volume of mulch film waste and the unit price for mulch film storage ($UC_{storage}$).

$$C_{storage} = \theta \times UQ_{mulching} \times S_{mulching} \times \eta \times UC_{storage} \tag{15}$$

where $\eta$ is the conversion coefficient between mulch film waste's volume and weight.

(7) Sludge removal costs

The treatment of mulch film produces waste such as sludge. The removal of the waste incurs relevant costs. $C_{sludge\ removal}$ is a function of the sludge's weight and unit removal price ($UC_{sludge\ removal}$).

$$C_{sludge\ removal} = Q_{sludge} \times UC_{sludge\ removal} \tag{16}$$

(8) Tax

Mulch film recycling enterprises are responsible for paying the corresponding taxes as required. According to "VAT Preferences Catalogue of Products and Services for Resources Comprehensive Utilization" [29], mulch film recycling is eligible for a 100% instant VAT refund policy. Therefore, $C_{tax}$ only includes income tax in this study.

$$C_{tax} = PBT \times \tau \tag{17}$$

where $PBT$ is the profit before tax, and $\tau$ is the rate of income tax.

### *2.3. Benefits of Mulch Film Management*

The benefits of mulch film management ($B_{management}$) encompass economic gains and external benefits [30]. Generally, the benefits consist of four main components.

Firstly, mulch film application leads to increased crop yields, resulting in economic benefits ($B_{increased\ yield}$). These are primarily associated with the potential increase in yield of different crops with various mulch films. The cropping area within the study region is 20,304.5 thousand hectares, with corn, potato, and cotton collectively accounting for 50.38% of the total [18]. These three crops are the predominant mulching crops in China. Hence, the three crops are considered target mulching crops for calculation.

$$B_{increased\ yield} = IY_{crop} \times S_{crop} \times UP_{crop} \tag{18}$$

where $IY_{crop}$ represents the potential increase in yield of crop $i$ after mulching with mulch film $j$, $S_{crop}$ is the area of crop $i$ with mulch film $j$, and $UP_{crop}$ is the market price of crop $i$. $i$ = 1, 2, 3 represents corn, potato, and cotton, respectively, and $j$ = 1, 2, 3 represents conventional film, thicker film, and biodegradable film, respectively.

Secondly, there are economic advantages introduced by selling generated byproducts ($B_{generated\ byproduct}$). These primarily refer to regenerated plastic pellets. $B_{generated\ byproduct}$ is related to the quantity of regenerated plastic pellets and their unit price ($UP_{generated\ byproduct}$).

$$B_{generated\ byproduct} = \theta \times UQ_{mulching} \times S_{mulching} \times \mu \times UP_{generated\ byproduct} \tag{19}$$

where $\mu$ is the conversion coefficient between mulch film waste and regenerated plastic pellets.

Thirdly, products regenerated through waste recycling offer external benefits. These products reduce raw material consumption and, correspondingly, prevent the release of

GHG emissions from the manufacturing of products ($B_{products\ avoidance}$). This value is mainly calculated based on the quantity of regenerated plastic pellets and the GHG emissions ($GHG_{plastics}$) released during their manufacture.

$$B_{products\ avoidance} = \theta \times UQ_{mulching} \times S_{mulching} \times \mu \times GHG_{plastics} \quad (20)$$

Lastly, there are the external benefits of recycling and substitution ($B_{recycling\ and\ substitution}$). These refers to the reduction in GHG emissions resulting from avoiding improper disposal of plastic waste through the recycling of thicker film and the substitution of this with biodegradable film. $B_{recycling\ and\ substitution}$ is determined by the amount of plastics that are prevented from being inappropriately disposed and the difference in GHG emissions.

$$B_{recycling\ and\ substitution} = \theta \times UQ_{mulching} \times S_{mulching} \times \mu \times GHG_{emission\ gap} \quad (21)$$

Thus, $B_{management}$ can be expressed as follows:

$$B_{management} = B_{increased\ yield} + B_{generated\ product} + B_{product\ avoidance} + B_{recycling\ and\ substitution} \quad (22)$$

The cost–benefit model of mulch film management is summarized in Figure 3.

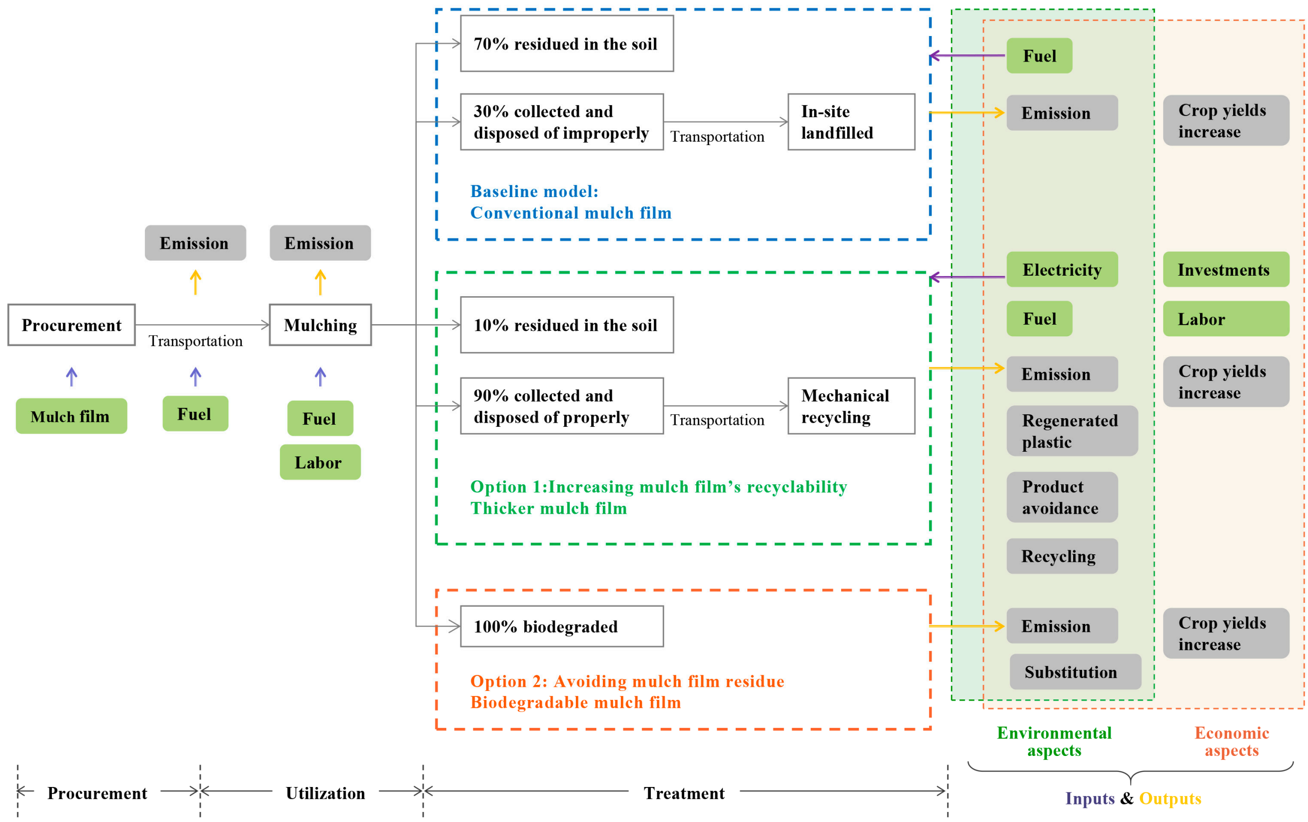


**Figure 3.** The boundary of mulch film management in the study.

## 2.4. Data

### 2.4.1. Scenario Assumption of Mulch Film Application Area

In the study, the mulch film management area follows the policy plan of "mulch film scientific utilization and recycling" as the reference for scenario assumptions. Considering the application area of thicker film and biodegradable film, three scenarios are developed, as shown in Table 1.

**Table 1.** Scenario description and required management fund estimation.

| Scenario | Background of Simulation | Area of Mulch Film Management | Cost of Mulch Film Management | |
|---|---|---|---|---|
| | | | Million CNY | Million USD |
| Business as usual | In March 2022, the Chinese government launched the "mulch film scientific utilization and recycling" pilot demonstration nationwide in 9 key mulch film utilization provinces (autonomous regions). The initiative supports the promotion of the application of thicker film on 3.3 million hectares and biodegradable film on 0.3 million hectares. | In the study region, 2.0 million hectares of thicker film and 106.7 thousand hectares of biodegradable film have been introduced, while the rest of mulching farmland applies conventional film. | 1107.0 | 155.0 |
| Management policy smoothly progressed | According to the pilot demonstration plan, environmentally friendly mulch film management will be further intensified, striving to promote the application of 13.3 million hectares of thicker film and 2.0 million hectares of biodegradable film by 2025. | In the study region, thicker film is applied to 2.5 million hectares of cotton and 6.7 million hectares of corn, while biodegradable film is applied to 1.0 million hectares of potato. | 5917.2 | 828.4 |
| Ideal situation | Assuming that the plan is thoroughly implemented nationwide, thicker film is applied to crops such as cotton, corn, and vegetable, and biodegradable film is applied to crops such as potato, peanut, and garlic apply. | Nationally, thicker film will be applied to 3.0 million hectares of cotton, 43.1 million hectares of corn, and 22.4 million hectares of vegetable, while biodegradable film will be applied to 4.5 thousand hectares of potato, 4.7 thousand hectares of peanut, and 0.8 million hectares of garlic. | 49,573.3 | 6940.3 |

### 2.4.2. Parameter Estimation for this Study

The parameter values from the study are summarized in Table 2.

**Table 2.** Parameter values in the study.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $UP_{mulching}$ | CNY 9.0/kg (USD 1.26/kg) for thicker film and conventional film; CNY 26.0/kg (USD 3.64/kg) for biodegradable film. | $PC_{enterprise}$ | 10,000 metric tons |
| $UQ_{mulching}$ | 92.0 kg/ha for conventional film; 138.0 kg/ha for thicker film; 126.0 kg/ha for biodegradable film. | $L_{employee}$ | 150 metric tons |
| $D_{transportation}$ | 10 km | $\beta$ | 30% |
| $UC_{transportation}$ | CNY 1.1/(ton·km) (USD 0.15/(ton·km)) | $Q_{material}$ | 2889,000 kW·h/year for electricity; 882 L/year for fuel; 10,000 ton/year for mulch film waste |
| $C_{fuel} + C_{labor}$ | CNY 450/ha (USD 63/ha) | $UP_{material}$ | CNY 1.80/kW·h (USD 0.25/kW·h) for electricity; CNY 7.49/L (USD 1.04/L) for fuel; CNY 600/ton (USD 84/ton) for mulch film waste. |
| $UP_{GHG}$ | CNY 59.68/ton (USD 8.36/ton) | $\eta$ | 5 |
| $Q_{fuel\ consumption}$ | 15 L/km for transportation; 7.5 L/ha for mulching. | $UC_{storage}$ | CNY 9/$m^3$ (USD 1.26/$m^3$) |
| $EF_{fuel}$ | 3.12 kg $CO_2$/L | $Q_{sludge}$ | 300 metric tons |
| $\theta$ | 90% | $UC_{sludge\ removal}$ | CNY 41.5/ton (USD 5.81/ton) |
| $UC_{collection}$ | CNY 600/ha (USD 84/ha) | $\tau$ | 25% |
| $D'_{transportation}$ | 10 km for conventional film; 100 km for thicker film; 0 km for biodegradable film. | $UP_{crop}$ | CNY 2.56/kg (USD 0.36/kg) for corn; CNY 2.49/kg (USD 0.35/kg) for potato; CNY 6.97/kg (USD 0.98/kg) for cotton. |
| $V_{initial}$ | Table S1 [31,32] | $IY_{crop}$ | Table S2 |
| $n$ | 15 years | $\mu$ | 0.25 |
| $\lambda$ | 5% | $UP_{regenerated\ product}$ | CNY 5975/ton (USD 836.5/ton) |
| $\alpha$ | 2% | $GHG_{plastics}$ | 2.67 kg $CO_2$/kg |
| $W_{local\ average}$ | CNY 59,739/year (USD 8386/year) | $GHG_{emission}$ | 6.53 kg $CO_2$/kg for landfill; −0.09 kg $CO_2$/kg for mechanical recycling; 3.9 $CO_2$/kg for biodegradable material degradation. |

Specifically, the concrete parameters are assigned the following values.

During the procurement stage, field surveys and the relevant literature indicate that 92.0 kg/ha of conventional film is required, while 138.0 kg/ha is required for thicker film [33]. Based on industry data, the price of plastic mulch film is CNY 9.0/kg (USD 1.26/kg). The utilization of biodegradable film which typically has a thickness of 0.010 mm, is 126.0 kg/ha, with a price of CNY 26.0/kg (USD 3.64/kg).

The transportation process refers to parameters of road traffic, with a unit cost of CNY 1.1/(ton·km) (USD 0.15/(ton·km)) [22]. The transportation distance from manufacturer to farmland is preset at 10.0 km. According to the field survey, the total economic cost of mulching is CNY 450/ha (USD 63/ha), with fuel consumption for transportation at 15.0 L/km and for mulching at 7.5 L/ha. Regarding the monetization of GHG emissions during fuel consumption, the carbon EF of fuel is calculated as 3.12 kg $CO_2$/L [34]. The emission price of $CO_2$ is based on the Fudan Carbon Price Index, calculated at the median price of the carbon emission quota in August 2023, which was CNY 59.68/ton (USD 8.36/ton) [35]. The monetization of carbon emissions for transportation and mulching are CNY 2.8/km (USD 0.39/km) and CNY 1.4/ha (USD 0.08/ha), respectively.

For treatment, the field survey showed that collecting and transporting mulch film waste to a treatment site costs CNY 600/ha (USD 84/ha). The recovery rate of mulch film waste, $\theta$, is 90% [10]. Fuel consumption for collection is estimated at 23.8 L/ha [36]. The value of $r$ is set at 8% [37]. Following government regulations and industry practices, the average depreciation life is calculated as 15 years, with a salvage rate of 5%. Rate $\alpha$ for equipment maintenance is 2% [22]. The average workload per employee is estimated by the enterprise manager to be 150 tons/year. The average wage is calculated to be CNY 59,739/year (USD 8386/year) under industry standards [38]. Rate $\beta$ for enterprise management costs is calculated to be 30% [22]. According to the enterprise survey, the electricity consumption for processing 1 metric ton of mulch film waste is 288.9 kW·h. The electricity price is CNY 1.8/kW·h (USD 0.25/kW·h) based on the industrial electricity price in the study region [39]. For an enterprise with a processing load of 17,000 metric tons of mulch film waste per year, the annual fuel consumption is 1500 L, with an average fuel price in the study region of CNY 7.5/L (USD 1.05/L) [40]. The industry survey indicates that the price of mulch film waste is CNY 600/ton (USD 84/ton). Briefly, 1 metric ton of mulch film waste from thicker film is about 5 $m^3$, denoted as $\eta$ equals 5. The enterprise survey indicates that approximately 300 metric tons of sludge will be generated for processing 10,000 metric tons of mulch film waste. The operating service charges catalog list specifies that the standard for removing non-residential waste is CNY 30–53/ton (USD 4.2–7.4/ton) in the study region [41]. The sludge removal cost is calculated employing a median value of CNY 41.5/ton (USD 5.81/ton).

Regarding the parameters for the benefits, the yields of corn, potato, and cotton after the application of different mulch films are taken from the studies of Cui [42], Wu [43], Zhang [44], and Liu [45]. Market prices for different crops are obtained from the National Grain and Material Reserves Bureau [46], the Information Center of the Ministry of Agriculture and Rural Affairs [47], and the China Cotton Information Network [48]. Enterprise surveys indicate that 4 metric tons of mulch film waste from thicker film can produce 1 metric ton of regenerated plastic pellets. Thus, the value of $\mu$ is calculated to be 0.25. The industry price of regenerated plastic pellets fluctuates in the range of CNY 4600–6550/ton (USD 644–917/ton) [49]. The study takes the medium value, which is CNY 5575/ton (USD 836.5/ton). Based on linear low-density polyethylene (LLDPE) standards, the carbon EF for plastic pellets is 2.67 kg $CO_2$/kg [50]. Plastic residues in the soil are resistant to degradation and gradually transform into microplastics over time, and the carbon EF associated with the process is 6.53 kg $CO_2$/kg [51]. The carbon emissions resulting from mechanical recycling amount to $-0.09$ kg $CO_2$/kg [36].

## 3. Results

### *3.1. Costs and Benefits of Environmentally Friendly Mulch Film Management*

Considering the procurement, utilization, and treatment of mulch film waste, the management cost for conventional film is CNY 1788.0/ha (USD 250.3/ha), with benefits amounting to CNY 4743.0/ha (USD 664.0/ha) (Table 3 and Figure 4). Due to the increase in the procurement cost and additional treatment cost, the management cost of thicker film is higher than that of conventional film. Within the management lifecycle of thicker film, there will be a cost PV of CNY 2567.6/ha (USD 359.5/ha) and a benefit PV of CNY 5776.4/ha (USD 808.7/ha). The management cost and benefits of biodegradable film are the highest of the three options, at CNY 3606.7/ha (USD 504.9/ha) and CNY 5851.3/ha (USD 819.2/ha), respectively.

In terms of management, conventional film waste is primarily landfilled after collection, so its treatment cost only involves the collection cost and transportation cost. Among the costs, the procurement cost of mulch film accounts for the most prominent proportion, at 46.3%. It is followed by the collection cost during the treatment stage, constituting 33.6% of the total. For thicker film, the management cost includes the procurement cost, utilization cost, and treatment cost. Similar to conventional film, the procurement cost contributes the highest share at 48.4%. The treatment cost comes next, at 38.7% of the total costs, among which the collection cost is the highest, while the mechanical recycling cost only represents 3.9% of the total. Regarding biodegradable film, the management cost consists only of two items, which are the procurement cost and utilization cost, since this film naturally degrades over time. Owing to the higher price of biodegradable film, 90.8% of its cost is attributed to the procurement cost.

**Table 3.** Results of the costs and benefits of different mulch films.

| | | | | **Baseline: Conventional Film** | | | **Option 1: Thicker Film** | | | **Option 2: Biodegradable Film** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **CNY** | **USD** | **%** | **CNY** | **USD** | **%** | **CNY** | **USD** | **%** |
| Costs | Utilization cost | | Procurement cost | 828.000 | 115.920 | 46.3 | 1242.000 | 173.880 | 48.4 | 3276.000 | 458.640 | 90.8 |
| | | | Transportation cost | 28.951 | 4.053 | 1.6 | 29.462 | 4.125 | 1.1 | 29.329 | 4.106 | 0.8 |
| | | | Mulching cost | 301.397 | 42.196 | 16.9 | 301.397 | 42.196 | 11.7 | 301.397 | 42.196 | 8.4 |
| | Treatment cost | | Collection cost | 601.397 | 84.196 | 33.6 | 601.397 | 84.196 | 23.4 | 0.000 | 0.000 | 0.0 |
| | | | Transportation cost | 28.237 | 3.953 | 1.6 | 293.086 | 41.032 | 11.4 | 0.000 | 0.000 | 0.0 |
| | | Mechanical recycling cost | Depreciation cost | 0.000 | 0.000 | 0.0 | 1.663 | 0.233 | 0.1 | 0.000 | 0.000 | 0.0 |
| | | | Equipment maintenance cost | 0.000 | 0.000 | 0.0 | 1.879 | 0.263 | 0.1 | 0.000 | 0.000 | 0.0 |
| | | | Labor cost | 0.000 | 0.000 | 0.0 | 23.493 | 3.289 | 0.9 | 0.000 | 0.000 | 0.0 |
| | | | Enterprise management cost | 0.000 | 0.000 | 0.0 | 7.048 | 0.987 | 0.3 | 0.000 | 0.000 | 0.0 |
| | | | Material cost_mulch film waste | 0.000 | 0.000 | 0.0 | 42.523 | 5.953 | 1.7 | 0.000 | 0.000 | 0.0 |
| | | | Material cost_electricity | 0.000 | 0.000 | 0.0 | 18.516 | 2.592 | 0.7 | 0.000 | 0.000 | 0.0 |
| | | | Material cost_fuel | 0.000 | 0.000 | 0.0 | 0.046 | 0.006 | 0.0 | 0.000 | 0.000 | 0.0 |
| | | | Mulch film waste storage cost | 0.000 | 0.000 | 0.0 | 3.189 | 0.446 | 0.1 | 0.000 | 0.000 | 0.0 |
| | | | Sludge removal cost | 0.000 | 0.000 | 0.0 | 0.088 | 0.012 | 0.0 | 0.000 | 0.000 | 0.0 |
| | | | Tax | 0.000 | 0.000 | 0.0 | 0.542 | 0.076 | 0.0 | 0.000 | 0.000 | 0.0 |
| | | | External cost_Mechanical recycling | 0.000 | 0.000 | 0.0 | 1.223 | 0.171 | 0.0 | 0.000 | 0.000 | 0.0 |
| | | | Subtotal | 1787.981 | 250.317 | / | 2567.552 | 359.457 | / | 3606.725 | 504.942 | / |
| Benefits | | | Benefit of crop yield increase | 4742.992 | 664.019 | 100.0 | 5546.657 | 776.532 | 96.0 | 5831.553 | 816.417 | 99.7 |
| | | | Benefit of generated byproduct | 0.000 | 0.000 | 0.0 | 175.613 | 24.586 | 3.0 | 0.000 | 0.000 | 0.0 |
| | | | Benefit of product avoidance | 0.000 | 0.000 | 0.0 | 5.019 | 0.703 | 0.1 | 0.000 | 0.000 | 0.0 |
| | | | Benefit of recycling and substitution | 0.000 | 0.000 | 0.0 | 49.080 | 6.871 | 0.8 | 19.753 | 2.765 | 0.3 |
| | | | Subtotal | 4742.992 | 664.019 | / | 5776.369 | 808.692 | / | 5851.307 | 819.183 | / |

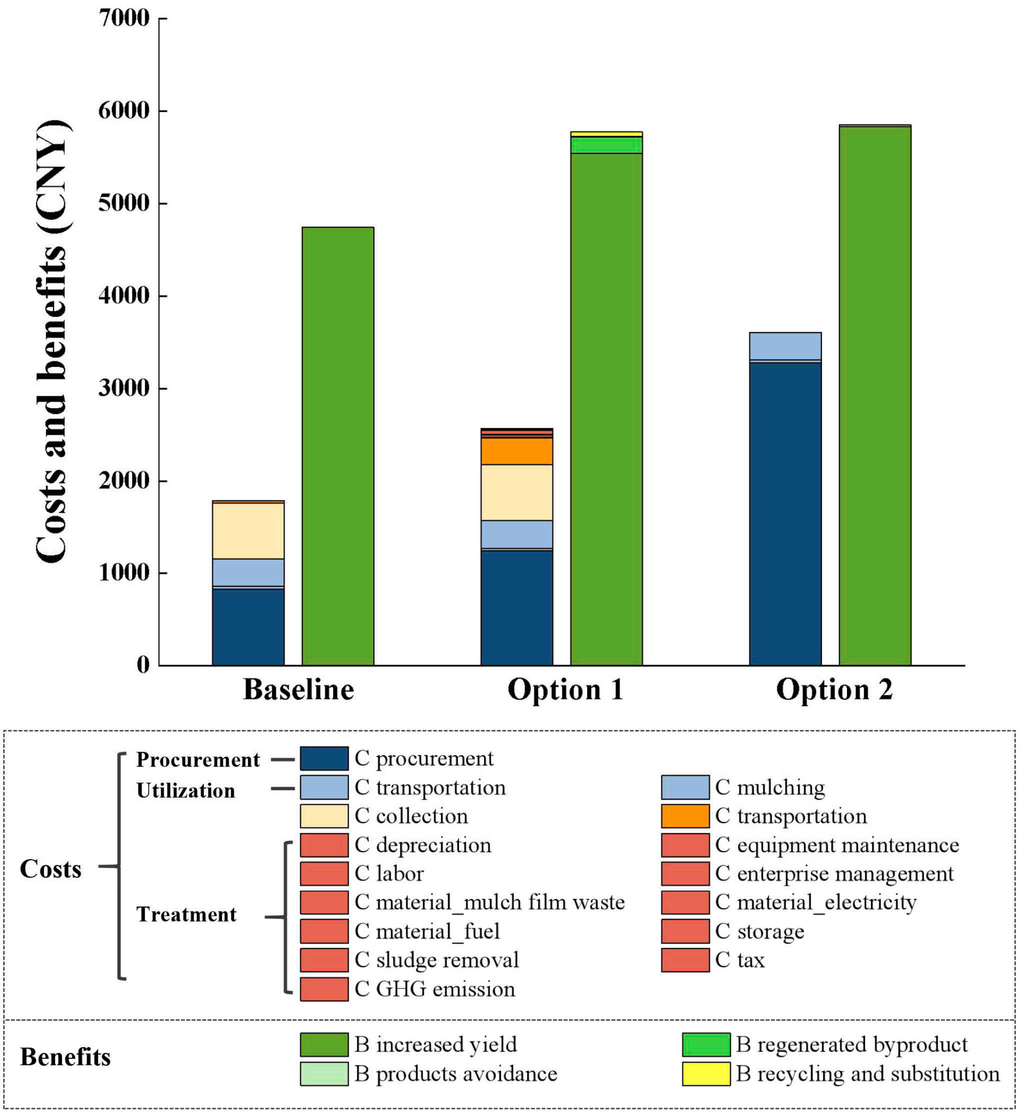


**Figure 4.** The costs and benefits of mulch film management.

Regarding the management benefits, the benefits of conventional film come entirely from the benefits of a crop yield increase. In the case of thicker film, regenerated plastic pellets yield both economic and environmental benefits. Among them, the benefits of a crop yield increase makes up a significant proportion of the management benefit, accounting for 96.0% of the total. The proportion of external benefits, which include the benefits of plastic avoidance and the benefits of recycling and substitution, is 0.9%. The benefits of biodegradable film include the benefits of crop yield increase and the benefits of recycling and substitution, with 99.7% of the total being derived from the former.

### 3.2. *Comprehensive Performance of Environmentally Friendly Mulch Film Management*

Applying conventional film yields a net benefit of CNY 2955.0/ha (USD 413.7/ha). Despite the increase in agricultural inputs, the payoff is quite considerable. The result affirms the recognized notion that mulch film application substantially contributes to increasing agricultural production and raising farmers' earnings [52]. Thicker film application can result in a net profit of CNY 253.8/ha (USD 35.5/ha), which is higher than that of conventional film, with a *BCR* of 2.19. Such a measure not only accomplishes the goal of increasing the recyclability of mulch film waste, thereby reducing threats that plastic poses in terms of soil safety and environmental pollution, but also guarantees food security and boosts agriculture income. The result indicates that the promotion of thicker film is a compelling initiative to promote mulch film management through and is the appropriate approach to strengthening agricultural non-point pollution management.

Although applying biodegradable film can lead to the greatest total benefits, its net benefit is lower than that of conventional film and thicker film, owing to its excessively high total cost, at CNY 2244.6/ha (USD 314.2/ha). The major contributors to the costs and benefits of biodegradable film application are the procurement costs and the benefits of crop yield increase. The procurement cost of biodegradable film far exceeds that of plastic mulch film, with its unit cost being 4.0 times higher than that of conventional film and 2.6 times higher than that of thicker film. Nevertheless, biodegradable film has not exhibited outstanding superiority over plastic mulch film regarding the promotion of crop yields, resulting in relatively lower net benefits. The result suggests that despite the unrivaled superiority of biodegradable film in terms of increased crop yield and the alleviation of mulch film waste, its promotion in actual agricultural production may encounter significant obstacles due to its economic unacceptability.

In summary, thicker film and biodegradable film can alleviate agricultural white pollution by enhancing mulch film waste's recyclability and eliminating the waste at the source. However, it is worthwhile to point out that mulch film management comes with considerable economic costs. Based on the three scenarios outlined in Section 4.1, for the application of mulch film, an annual investment of CNY 1107.0 million (USD 155.0 million) is required from the government or third-party financiers to sustain the management of the 2.14 million hectares of farmland for the pilot demonstration in the study region (Scenario 1). Assuming, in Scenario 2, that the management area is expanded to include all the three main mulch film crops in the study region, the funding requirement increases to CNY 5917.2 million/year (USD 828.4 million/year). Further, if the management area is expanded to the whole country and if the policy is adjustment to include more film-mulching crops, the annual management investment requirement will surge to CNY 49,573.3 million (USD 6940.3 million).

A sensitivity analysis is employed to evaluate the impacts of relevant factors in the study on the *NPV* of different mulch film management measures (Figure 5). The prices of biodegradable film, electricity, $CO_2$, and regenerated plastic pellets, and the crop yields are selected as the main factors for this analysis. Among them, the prices of biodegradable film and electricity decreased by 40% with a 10% change rate. The price of regenerated plastic pellets and crop yields saw a 20% decrease and a 20% increase, respectively, with a 10% change rate. The results demonstrate that fluctuations in crop yields have the most significant impact on the economic performance of different mulch film management measures. In particular, fluctuations in corn yield have a greater effect on the *NPV*. When applying thicker film, a 10% variation in corn and cotton yields will bring about 10.2% and 7.1% changes, respectively, in the *NPV* with Option 1. When applying biodegradable film, a 10% variation in corn and potato yields will result in 20.8% and 4.9% changes in the *NPV*, respectively, with Option 2. In addition, the price of biodegradable film is another primary factor affecting the economic performance observed under Option 2. When it increases by 10%, the *NPV* of Option 2 increases by 14.4%. Comparatively, fluctuations in the prices of electricity, $CO_2$, and regenerated plastic pellets exhibit minor impacts on the economic performance of different mulch film management measures.

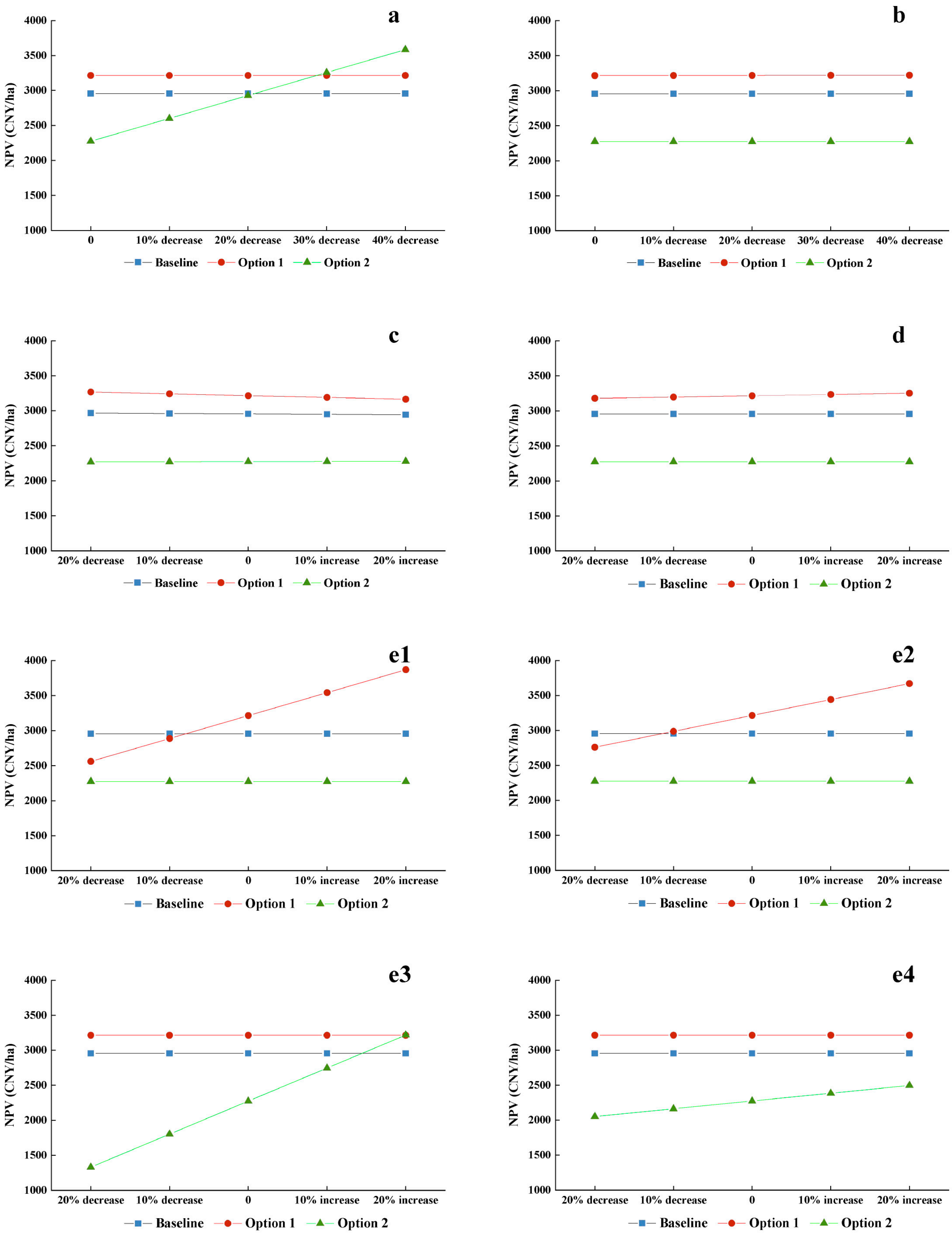


**Figure 5.** The results of sensitivity analysis: (**a**) the price of biodegradable film; (**b**) the price of electricity; (**c**) the price of $CO_2$; (**d**) the price of regenerated plastic pellets; (**e1**) the corn yield with the application of thicker film; (**e2**) the cotton yield with the application of thicker film; (**e3**) the corn yield with the application of biodegradable film; (**e4**) the potato yield with the application of biodegradable film.

## 4. Discussion

Mulch film management is a pressing issue in China. However, it is unsustainable to maintain the current subsidy standards for the widespread promotion of the initiative of mulch film scientific utilization and recycling. Efforts should be made to optimize subsidy policies for mulch film management to maximize the effectiveness of government resources in agricultural white pollution control. Scientifically accounting for the cost–benefit performance of mulch film management measures allows us to provide a scientific reference for developing rational mulch film management policies.

### *4.1. Thicker Film Application Is Cost-Effective, and the Key to The Promotion of Its Use Lies in Improving Farmers' Attitudes and Optimizing Subsidy Dimensions*

As stated in the economic analysis in Section 3.2, thicker film presents notably positive economic benefits compared with conventional film. Theoretically, thicker film can be adopted proactively, owing to its economic advantages, even without external subsidies. While the government subsidy of CNY 450/ha (USD 63/ha) for thicker film may stimulate its application, it results in somewhat inefficient utilization of fiscal resources. Indeed, farmers are inclined to purchase thicker film only when its usage costs are subsidized and essentially equivalent to those of conventional film. Bridging the gap between theory and reality can guide the government to optimize its policies for mulch film management.

The results of Section 3.1 on costs and benefits reveals that the cost disparity between thicker film and conventional film manifests primarily in the procurement and treatment phases. In the procurement phase, thicker film incurs an additional cost of CNY 414.0/ha (USD 58.0/ha) compared with that of conventional film. The benefits, in contrast, are not realized until the crop is harvested in the following year, signifying a considerable time lag. Given the considerable uncertainty about the future, especially for agricultural production, which faces a significant "weather-dependent" dilemma, farmers with bounded rationality may prioritize immediate economic loss [53]. In other words, farmers may experience psychological resistance when faced with the need to incur a higher cost to purchase thicker film. Therefore, it is imperative to promote widespread knowledge of the advantageous outcomes of applying thicker film, particularly in terms of its ability to generate significant economic gains, to elevate farmers' comprehensive and scientific understanding of mulch film management.

Regarding the treatment phase, the results of the cost–benefit analysis of mulch film recycling, which was conducted for the 15-year life cycle of the recycling enterprise, show an *NPV* of CNY 1.4 million (USD 0.2 million) and a *BCR* of 1.01. The indicators demonstrate that the mulch film recycling project will yield more favorable outcomes than expected (at a social discount rate of 8%). Despite the project's profitability, previous studies have shown that enterprises can operate steadily when the *BCR* remains at 1.1–1.2 [54]. Given the current costs and benefits of mulch film recycling, enterprises lack sufficient motivation to sustain mulch film recycling activities. To achieve a *BCR* of 1.1, an annual subsidy of CNY 698,564 (USD 97,799) is required for an enterprise with an annual processing capacity of 10,000 metric tons. To achieve the goal of agricultural plastic waste management through the widespread adoption of thicker film, the backend of management—waste treatment—cannot be ignored. Future policies need to appropriately shift their focus on the treatment phase, exploring incentives to provide enterprises with more impetus to carry out mulch film recycling activities.

### *4.2. Biodegradable Film Application Will Require Continuous External Subsidies, Cost Reductions and Efficiency Increases in the Future*

Despite the functional advantages of biodegradable film over conventional film and its unparalleled superiority in mitigating plastic pollution [55], it does not outperform conventional film regarding economic performance. In the absence of external subsidies, its widespread adoption in agricultural production may encounter significant obstacles due to its economic infeasibility, aligning with the significant barriers of other biodegradable materials [56]. As previously stated, in order to promote biodegradable film use and mitigate users' resistance to its utilization, a price subsidy of CNY 1800/ha (USD 252/ha) was proposed as sufficient to cope with the additional pressure costs of purchasing it [57]. The result of the economic analysis in Section 3.2 indicates that, considering the benefits introduced by different types of mulch film application, the benefit discrepancy between biodegradable film and conventional film is CNY 710.4/ha (USD 99.5/ha). The present subsidy for biodegradable film far exceeds the benefit losses incurred by its application. The government could optimize the subsidy for biodegradable film based on the cost–benefit performance of the different types of mulch films applied. It is imperative to adjust the subsidies moderately, ensuring they are appropriately higher than the incurred economic losses to guarantee effective incentives for farmers' adoption of biodegradable film, while keeping the allocation of financial resources reasonable.

In addition, the weaknesses of biodegradable film in terms of mechanical performance and hydrophilicity restrict its applicability to specific crops with a short growth cycle [58]. Biodegradable film's duration and degree of degradation vary depending on variations in natural circumstances across different regions [59]. Currently available biodegradable film does not contain suitable degradation characteristics, a reasonable start-up period, or a degradation rate suited to different crops' growth. In light of this, future considerations may lean toward moderately favoring policy towards mulch film manufacturing enterprises, leveraging the incentivizing effect of government subsidies to stimulate increased investment in research and development (R&D). Through scaled production and technological advancements to lower production costs and enhance product performance, there lies the potential for the more effective promotion of biodegradable film and for the alleviation of agricultural white pollution.

### *4.3. Sustainable Mulch Film Management Entails Developing a Mechanism to Realize the External Benefits of Management and of Innovating a Governance Landscape*

It should be noted that this study considers the environmental benefits of recycling thicker film and substituting conventional film with biodegradable film. The results of Section 3.1 on costs and benefits indicate that applying 1 hectare of thicker film and biodegradable film instead of conventional film can yield external benefits amounting to CNY 54.1 (USD 7.6) and CNY 19.8 (USD 2.8), respectively. However, there is no mechanism through which to monetize the external benefits of mulch film management in reality. These under-appreciated benefits could have critical implications for increasing the viability of agricultural white pollution control and reducing the burden of external funding requirements. Therefore, the incorporation of mulch film management into the carbon trading market should be actively explored to provide more market incentives and policy support by transforming environmental advantages into economic gains. Generally, it is imperative to establish a comprehensive carbon emission and carbon sink accounting system for the life cycle of mulch film management. The sources of GHGs throughout the lifespan of mulch film management are extensive and scattered, leaving them complicated to quantify precisely. Hence, building upon this study, further research into and the refinement of more scientifically grounded methodologies are warranted, ensuring that the monitoring, accounting, and evaluation of emissions and the carbon sink in mulch film management processes are more standardized and regulated. Subsequently, it would be timely to explore the pilot demonstration for carbon trading in mulch film management. Following the principles of pilot precedence and gradual progression, carbon trading projects for mulch film management should be conducted in regions abundant in mulch film application carbon emission and carbon sink resources, providing replicable experiences for promoting nationwide agricultural plastic carbon trading and advancing sustainable agricultural white pollution control.

In addition, the ecological environment is a quasi-public good. In addressing agricultural white pollution, sole reliance on either government intervention or market mechanisms may lead to failure. As the relationship between economic development and environmental conservation deepens, polycentric governance will facilitate the increased sharing of social responsibilities and increase governmental efficiency compared with that of single-subject governance. Within the polycentric governance framework, the government, the market, and societal entities including organizations and the public, form an inseparable triad (Figure 6). In a polycentric governance structure, the government predominantly assumes an intermediary role, formulating a macro-framework of a multicentric landscape for agricultural white pollution and establishing behavioral norms for participating entities. The market, guided by the principles of supply and demand, engages in producing environmentally friendly mulch film and recycling mulch film waste. This allows for the achievement of an equilibrium between supply and demand, and enhances the efficiency of public goods provision. The public, on the one hand, possesses legally authorized rights to environmental information, decision-making, and supervision. On the other hand, as beneficiaries of agricultural pollution control, members of the public must assume the responsibilities of environmental protection and pollution control. Given the growing environmental consciousness of the large population base, public support introduces great prospects in terms of promoting agricultural white pollution control. Social organizations are significant forces in societal governance, being entitled to environmental investigation and supervision rights. In agricultural white pollution governance, social organizations can foster cooperative partnerships and establish public norms through democratic negotiations with other entities, thereby realizing diversified interests among multiple stakeholders.

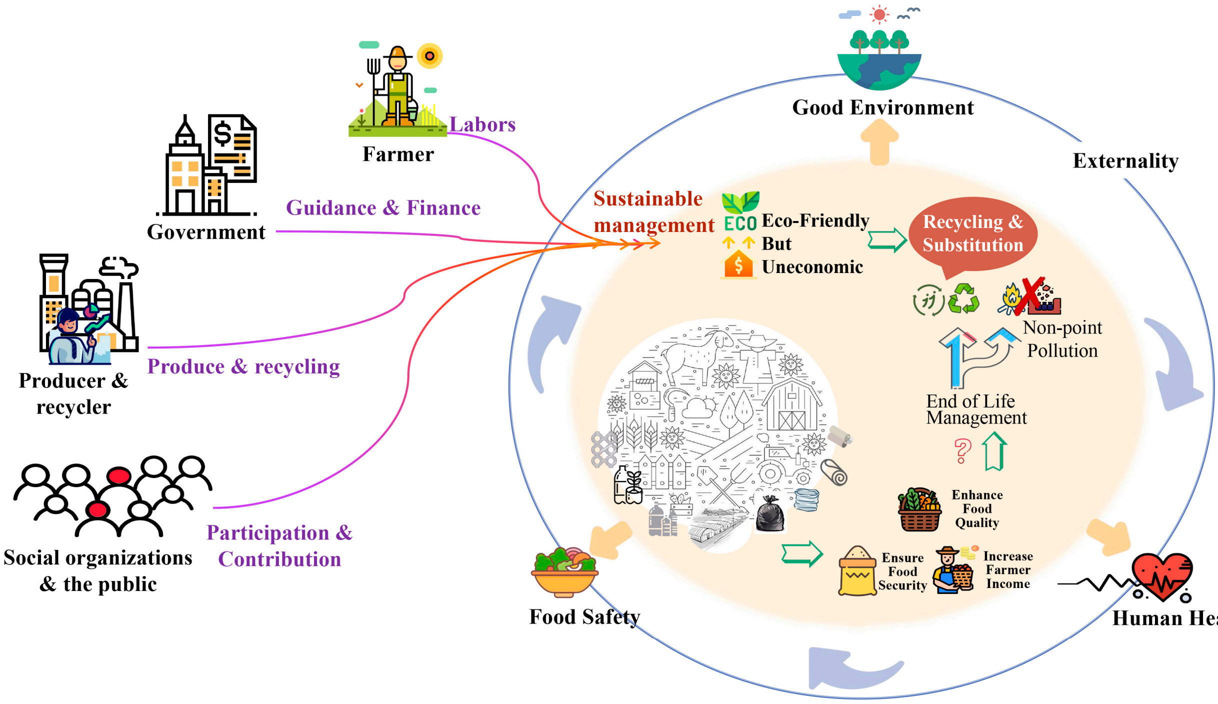


**Figure 6.** Polycentric governance for mulch film management.

## 5. Conclusions

This study conducts a cost–benefit analysis of mulch film management in China. It specifically examines two environmentally friendly mulch film management measures: the application of thicker film and that of biodegradable film. The results indicate that applying thicker film is economically feasible, with substantial potential for expansion. However, there are certain limitations to the current government subsidies for it. Theoretically, thicker film can be implemented spontaneously without financial support due to its economic advantages, and since the current government subsidy standard for it results in a certain degree of government economic resource waste. Furthermore, the reason for its inadequate promotion is the lack of recognition of its benefits in waste treatment, which is a weak point, as well as the fact that it is not adequately supported by the current subsidies. Comparatively, biodegradable film is unprofitable due to its high material costs, and its further development requires standardized external funding support. Nevertheless, the current policy exhibits high subsidy standards and leads to financially inefficient utilization. In addition, deficiencies in the product's performance restrict its universal application. In this regard, to promote environmentally friendly mulch film management measures, it is imperative to raise farmers' comprehensive knowledge of them, optimize government subsidy standards and dimensions for management, and explore strategies to reduce the costs and increase the efficiency of mulch films. Further analysis reveals the need to advance sustainable mulch film management by developing a carbon trading mechanism to internalize the external benefits of the management, and to introduce funding sources for sustainable agricultural white pollution control.

This study primarily relies on case studies, such as crop yield statistics obtained from the application of various mulch films, which may vary depending on region, climate, and agronomic practices. The sensitivity analysis result also reveals that variations in crop yields have a significant impact on the economic performance of mulch film management. Future studies on the impact of diverse mulch films on crop yields can provide more precise references. In addition, as this study emphasizes the economic feasibility of mulch film management, the external impacts described are simplified to some extent. For example, GHG emissions are only based on $CO_2$ emissions for accounting. Moreover, this study does not consider the environmental impacts of mulch film manufacturing, and the differences in GHG emissions between biodegradable materials and plastics during production may also influence the proposed film's cost-effectiveness [58]. Future studies could expand the study's boundaries and employ life cycle assessment (LCA) to systematically evaluate the environmental and economic performance of different mulch film management measures.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture14071081/s1: Table S1: Fixed assets in the mechanical recycling of mulch film waste; Table S2: Parameter of $IY_{crop}$ in the study; Table S3: Yields for corn in different mulching conditions; Table S4: Yields for potato in different mulching conditions; Table S5: Yields for cotton mulching with conventional film and thicker film; Table S6: Yields for cotton mulching with conventional film; Table S7: Yields for cotton in different mulching conditions.

**Author Contributions:** Conceptualization, A.H. and C.Y.; methodology, A.H., A.L. and T.D.; software, A.H.; validation, A.L.; investigation, A.H.; resources, C.Y.; data curation, A.H.; writing—original draft, A.H.; writing—review and editing, C.Y., A.L. and T.D.; supervision, C.Y., A.L. and T.D.; funding acquisition, C.Y. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data used to support the findings of this study can be made available by the corresponding author upon request.

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